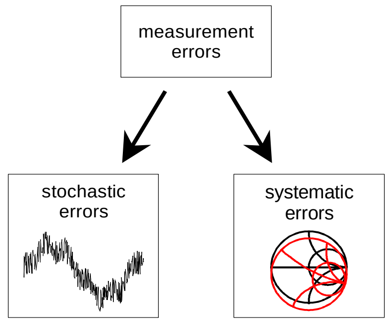
Measurement Accuracy of Vector Network Analysis

Thilo Bednorz

VNA Measurement and Accuracy

Error sources occuring
with VNA measurement



- **Unpredictable**
- **No correction**

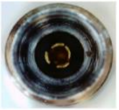
- Signal to noise
- Compression of the receiver
- Stability of instrument
- Stability and repeatability of test setup

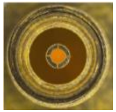
- **Errors due to limited performance of the VNA and test setup**
  - Mismatch of the test ports
  - Transmission errors due to losses of the testset
- **Can be reduced by „system error correction“ („user calibration“)**

Stochastic Errors

Setup:

- Repetability of the connectors
- Phase and magnitude stability of the cables





Instrument

- Compression
- Thermal drift
- Noise
- Repeatability

- Stochastic errors are not predictable and cannot be reduced by error correction methods
- They can only be reduced by improved hardware for steup and instrumentation

What indicates Accuracy in the Data Sheet

- Measurement Accuracy
  - Conditional guidance based upon specific criteria
- Effective System Data
  - RF instrument parameters (such as directivity, port matching, tracking), after applying the system error calibration and correction.
  - Depends on the instrument, setup parameters and calibration kit
- Factory calibrated system data
  - Default effective system data using a calibration stored in the factory
- Raw Performance of the test ports
  - The uncorrected HW properties, which take effect to the physical power waves
  - It is the physical match the DUT sees during the measurement

Directivity
Source Match
Reflection Tracking
Transmission Tracking
Load Match

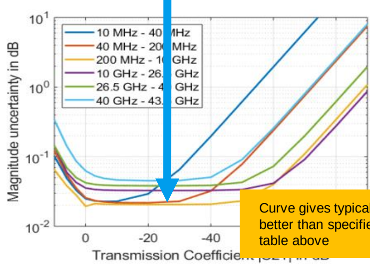
Data Sheet Measurement Accuracy:

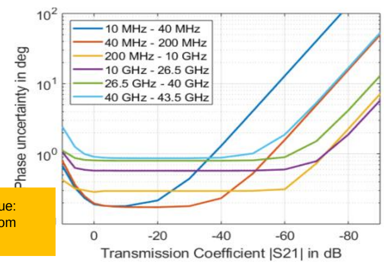
Transmission measurement accuracy after Calibration

Measurement accuracy of the R&S®ZNA43

The data below is valid between +18 °C and +28 °C, provided the temperature has not varied by more than 1 °C after calibration. Validity of the data is conditional on using an R&S®ZN-Z229 calibration kit in order which to achieve the effective system data specified below. Frequency points, measurement bandwidth and sweep time have to be identical for measurement and calibration (no interpolation of the calibration). Specifications are based on a matched DUT for transmission measurements and on an isolated DUT for reflection measurements. In both cases, a measurement bandwidth of 10 Hz and a nominal source power of 0 dBm apply.

Accuracy of transmission measurements		Magnitude in dB	Phase in °
> 200 MHz to 10 GHz	0 dB to –30 dB	0.04	0.7
	< –30 dB to –40 dB	0.05	0.8
	< –40 dB to –50 dB	0.05	0.8
	< –50 dB to –60 dB	0.09	1.0



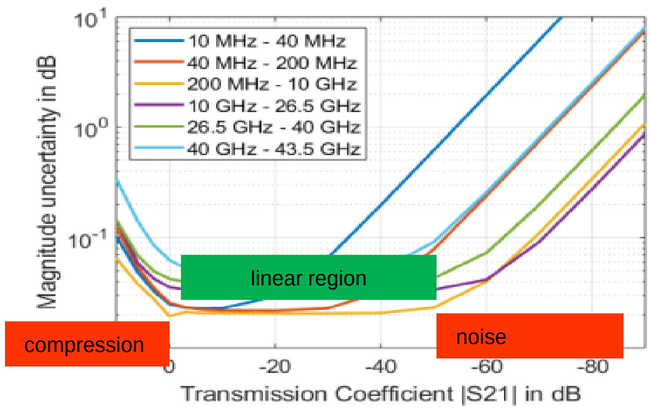


Curve gives typical value: better than specified from table above

What Accuracy in the Data Sheet means

- Well matched DUT, no errors due to port mismatch
- Main error sources are
  - Compression
  - Linearity, A/D converter errors
  - Noise

n a matched DUT for transmission measurements and on an isc
nt bandwidth of 10 Hz and a nominal source power of 0 dBm ap



Data Sheet effective System Data

Effective system data depend on

- Quality of calibration
- Used calibration technique
- Instrument settings

Effective system data of ZNA

The data below is valid between +18 °C and +28 °C, provided the temperature has not varied by more than 1 °C after calibration. Frequency points, measurement bandwidth and sweep time have to be identical for measurement and calibration (no interpolation of the calibration). The data is based on a measurement bandwidth of 10 Hz.

R&S®ZNA43 calibrated with R&S®ZN-Z229 calibration kit	10 MHz to 40 MHz		> 40 MHz to 10 GHz		> 10 GHz to 26.5 GHz	
	Specification	Typical	Specification	Typical	Specification	Typical
Directivity in dB	42	45	45	48	42	45
Source match in dB	[illegible]	41	41	44	40	43
Load match in dB	[illegible]	44	44	47	41	44
Reflection tracking in dB	[illegible]	0.03	0.03	0.02	0.04	0.03
Transmission tracking in dB	[illegible]	0.03	0.02	0.01	0.03	0.02

Effective system data of R&S®ZN-Z229 calibration kit

The specified effective system data are established after performing a suitable system error calibration, e.g. TOSM, at a R&S®ZNA, R&S®ZVA, R&S®ZVB, or R&S®ZVT vector network analyzer, using the characteristic data of the calibration kit, which are stored on a provided USB flash drive. This data is valid between +18 °C and +28 °C, at a measurement bandwidth of 10 Hz and a nominal power of 0 dBm at the calibration ports. The calibration kit is fully functional down to 0 Hz, with effective system data as specified below, although the data is only verified for frequencies as stated. Calibration frequencies: DC; from 50 MHz to 26.5 GHz in 50 MHz steps.

Directivity	0 Hz to 10 GHz	> 45 dB, typ. 48 dB
	10 GHz to 26.5 GHz	> 42 dB, typ. 45 dB
	26.5 GHz to 40 GHz	> 38 dB, typ. 41 dB
	40 GHz to 43.5 GHz	> 38 dB (meas.)
Source match	0 Hz to 10 GHz	> 41 dB, typ. 44 dB
	10 GHz to 26.5 GHz	> 40 dB, typ. 43 dB
	26.5 GHz to 40 GHz	> 36 dB, typ. 39 dB
	40 GHz to 43.5 GHz	> 36 dB (meas.)
Reflection tracking	0 Hz to 10 GHz	< 0.03 dB, typ. 0.02 dB
	10 GHz to 26.5 GHz	< 0.04 dB, typ. 0.03 dB
	26.5 GHz to 40 GHz	< 0.04 dB, typ. 0.03 dB
	40 GHz to 43.5 GHz	< 0.06 dB (meas.)
Load match	0 Hz to 10 GHz	> 44 dB, typ. 47 dB
	10 GHz to 26.5 GHz	> 41 dB, typ. 44 dB
	26.5 GHz to 40 GHz	> 37 dB, typ. 40 dB
	40 GHz to 43.5 GHz	> 37 dB (meas.)
Transmission tracking	0 Hz to 10 GHz	< 0.02 dB, typ. 0.01 dB
	10 GHz to 26.5 GHz	< 0.03 dB, typ. 0.02 dB
	26.5 GHz to 40 GHz	< 0.04 dB, typ. 0.03 dB
	40 GHz to 43.5 GHz	< 0.05 dB (meas.)

Data Sheet Factory calibrated System Data

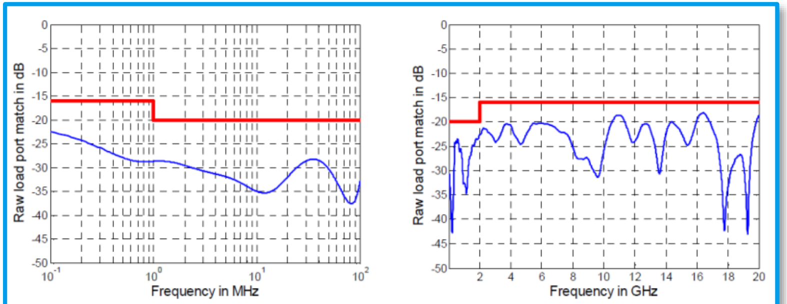
Factory-calibrated system data

This data is valid between +18 °C and +28 °C. It is based on a source power of –10 dBm and a measurement bandwidth of 1 kHz.

Directivity	9 kHz to 50 kHz	> 20 dB, typ. 35 dB
	50 kHz to 4.5 GHz	> 30 dB, typ. 50 dB
	4.5 GHz to 10 GHz	> 30 dB, typ. 50 dB
	10 GHz to 20 GHz	> 25 dB, typ. 35 dB
	20 GHz to 35 GHz	> 20 dB, typ. 20 dB
	35 GHz to 40 GHz	> 15 dB, typ. 20 dB
Source match	9 kHz to 50 kHz	> 20 dB, typ. 35 dB
	50 kHz to 4.5 GHz	> 30 dB, typ. 50 dB
	4.5 GHz to 10 GHz	> 30 dB, typ. 50 dB
	10 GHz to 20 GHz	> 25 dB, typ. 35 dB
	20 GHz to 35 GHz	> 20 dB, typ. 20 dB
	35 GHz to 40 GHz	> 15 dB, typ. 20 dB
Reflection tracking	9 kHz to 20 GHz	< 0.5 dB, typ. 0.1 dB
	20 GHz to 40 GHz	< 0.5 dB, typ. 0.1 dB
Transmission tracking	9 kHz to 20 GHz	< 0.5 dB, typ. 0.1 dB
	20 GHz to 40 GHz	< 0.5 dB, typ. 0.1 dB
Load match of the R&S®ZNB4 and the R&S®ZNB8	9 kHz to 50 kHz	> 10 dB, typ. 15 dB
	50 kHz to 8.5 GHz	> 20 dB, typ. 25 dB
Load match of the R&S®ZNB20	100 kHz to 1 MHz	> 16 dB, typ. 20 dB
	1 MHz to 2 GHz	> 20 dB, typ. 23 dB
	2 GHz to 20 GHz	> 16 dB, typ. 19 dB
Load match of the R&S®ZNB40	10 MHz to 50 MHz	> 15 dB, typ. 18 dB
	50 MHz to 2 GHz	> 20 dB, typ. 22 dB
	2 GHz to 6 GHz	> 16 dB, typ. 18 dB
	6 GHz to 10 GHz	> 12 dB, typ. 14 dB
	10 GHz to 20 GHz	> 10 dB, typ. 12 dB
	20 GHz to 40 GHz	> 8 dB, typ. 10 dB

Data Sheet raw Test Port performance:

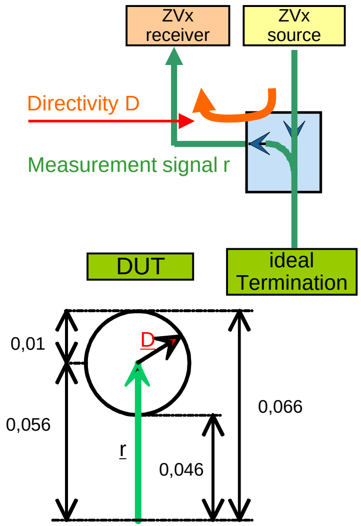
- Has low impact on the accuracy after full error calibration
- Impacts parameters that are not effected by error model
  - Harmonics
  - Spurios (e.g. mixer)



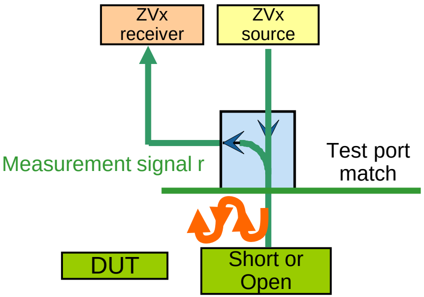
Raw load port match versus frequency for the R&S®ZNB20.

Sytematic Errors for Reflection Measurements

Error due to Directivity



Error due to Test Port Match

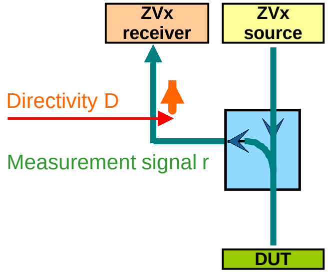


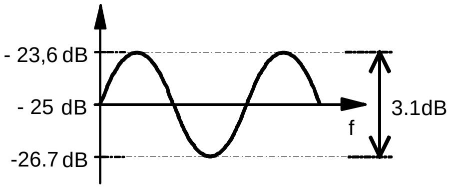
Reflection Measurement

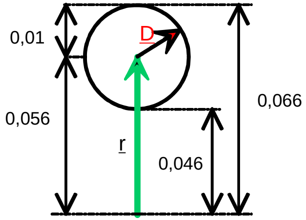
3 error terms:

- D := Directivity
- Γ :=Port Match
- T := Transmission loss

Error Estimation for Reflection Measurements







DUT return loss: -25 dB (= 0,056)
Directivity of bridge: 40 dB (=0,01)
Min. value: 0.056 - 0.01 = 0.046 (-26.7 dB)
Max. value: 0.056 + 0.01 = 0.066 (-23.6 dB)

Measurement uncertainty:
-1.7 dB to 1.4 dB

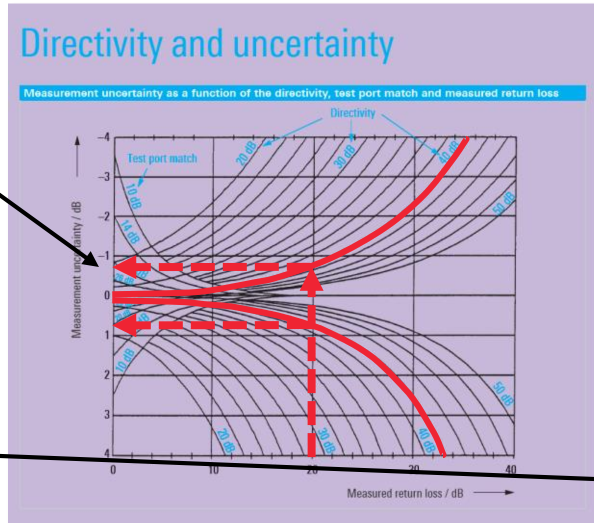
Error Estimation Example

- Directivity 40 dB
- Match DUT 20 dB
- Error 0.9 dB pk-pk

- Error estimation via graph

- General error estimation using the table

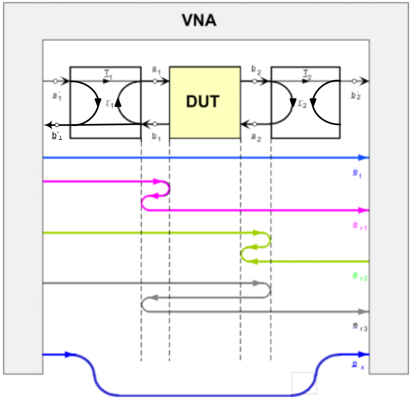
  - Error signal 20 dB below the measurement signal results in an error of 1 dB pk-pk
  - *Error signal 40 dB below the measurement signal results in an error of 0.1 dB pk-pk (not on the table)*



Signal to error signal	Measurement uncertainty	
|x| in dB	1 + |x| in dB	1 – |x| in dB
0	6.021	∞
1	5.535	–19.271
2	5.078	–13.737
3	4.649	–10.691
4	4.249	–8.658
5	3.876	–7.177
6	3.529	–6.041
7	3.207	–5.141
8	2.911	–4.410
9	2.638	–3.806
10	2.387	–3.302
11	2.157	–2.876
12	1.946	–2.513
13	1.755	–2.201
14	1.580	–1.933
15	1.422	–1.701
16	1.278	–1.499
17	1.148	–1.323
18	1.030	–1.169
19	0.924	–1.034
20	0.828	–0.915
21	0.742	–0.811
22	0.664	–0.719

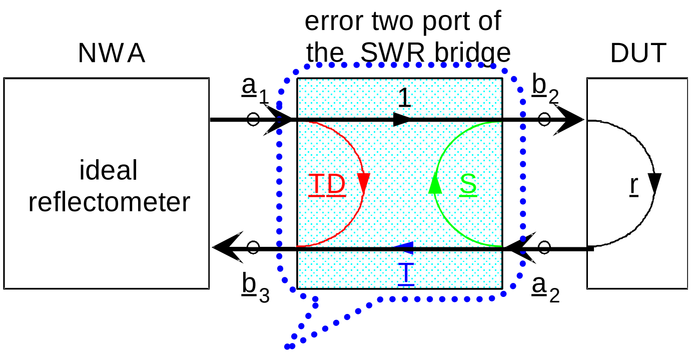
Systematic Errors of a Measurement in forward Direction

- Typical error terms:
  - Directivity D
  - Transmission tracking T
  - Reflection tracking T
  - Source match Γ
  - Load match Γ
  - Cross talk X_F
- Error terms are described by „error matrices“ (VNA assumed to be „ideal“)
- Task of System Error Correction:
  Evaluation of error terms for correction of measurement data



Error signals for a transmission measurement

Example: Calibration for Reflection measurements



$$\underline{b}_3 = \underline{T} \cdot \underline{D} \cdot \underline{a}_1 + \underline{T} \cdot \underline{b}_2 \cdot \underline{r}$$

$$\underline{b}_2 = \underline{a}_1 + \underline{b}_2 \cdot \underline{S} \cdot \underline{r}$$

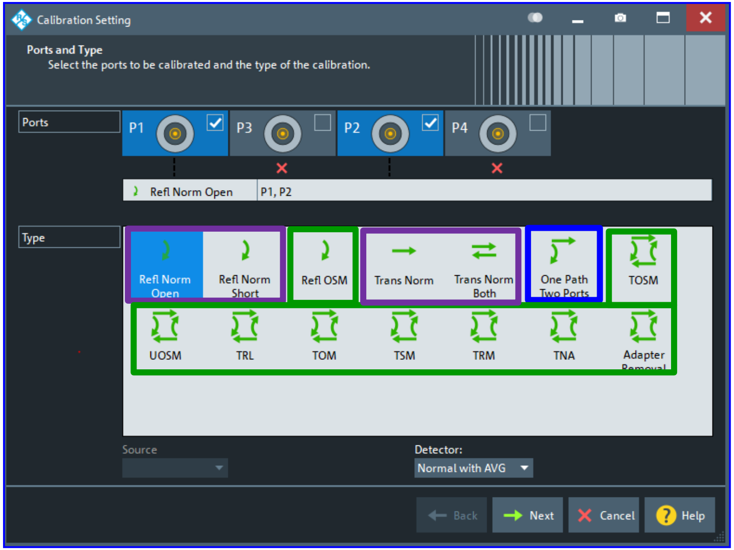
R : value of the DUT

r' : measured value

$$\boxed{\underline{r}' = \frac{\underline{b}_3}{\underline{a}_1} = \underline{T} \cdot \left(\underline{D} + \frac{\underline{r}}{1 - \underline{S} \cdot \underline{r}} \right)}$$

Applying 3 known calibration standards generates 3 equations with 3 unknown (error) parameters T, D, S, e.g. Open, Short and Match

Types of Calibration Techniques

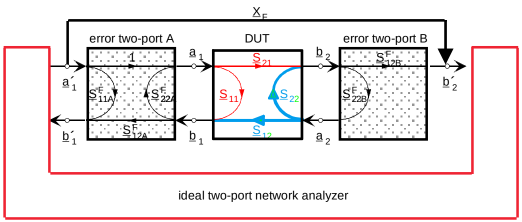


Types of Calibration Techniques

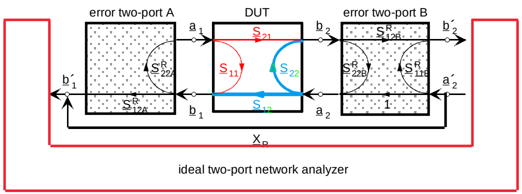
- Normalization
  - Transmission and reflection normalization
- One Path Two Port (OSM + Normalization)
  - For unidirectional test setups (e.g. pre-amplifier in the test set)
- Full One Port Calibration (OSM)
  - Allows corrected reflection measurements (S11, S22)
- Full Two Port Calibration
  - Bidirectional, corrects for all error terms
  - Allows corrected measurement of all S-parameters
  - Highest accuracy

TOSM - Classical Full Two-Port Calibration

Forward measurement



Reverse measurement



- Extension of the one port error model by 3 additional error terms for transmission measurement => 6 error terms
- Similar model for forward and reverse direction.

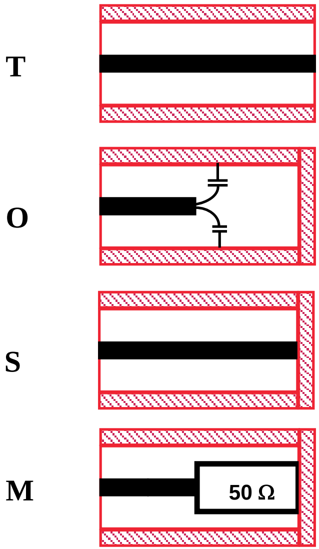
⇨ 12-term error model (TOSM)

- Disregarding crosstalk:

⇨ Reduction to 10-term model

- Frequently used due to historical reasons

TOSM - The classical Calibration Technique

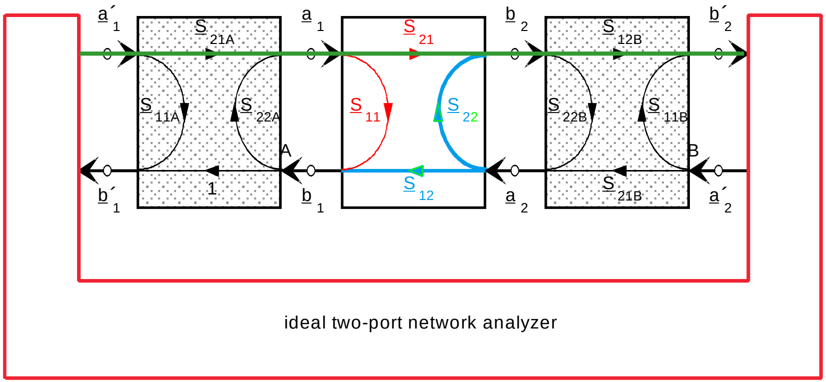


- T = *Through* *(50 Ω, el. length)*
- O = *Open* *(el. length, capacities, loss)*
- M = *Match* *(50 Ω)*

- *10 Error terms – 10 known Parameters*
  - *2 by Open P1; P2*
  - *2 by Short P1;P2*
  - *2 by MatchP1;P2*
  - *4 by Through P1-P2*

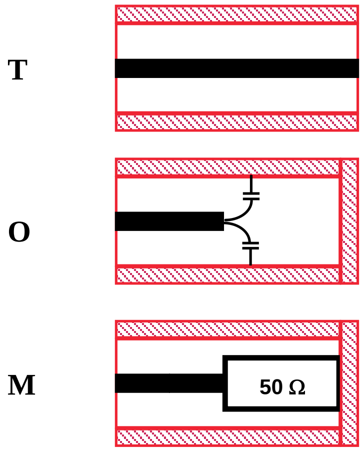
☹Characteristics of all standards required
☹Through standard assumed ideally matched
☹Effective Load match limited to match of the Through

Calibration Techniques with 3 Standards



- Error model with only 7 error terms
- Provided by all ZVA, ZVB, ZVT

TOM Calibration



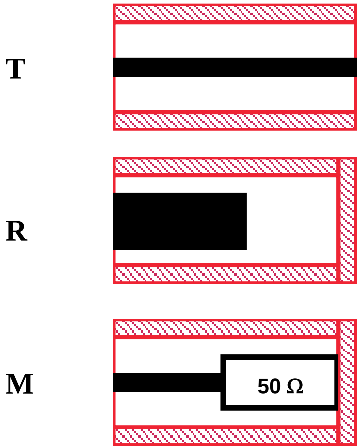
- T = *Through* *(50 Ω, el. length)*
- O = *Open* *(el. length, capacities, loss)*
- M = *Match* *(50 Ω)*

- *7 Error terms – 7 known Parameters*
  - *2 by Open P1; P2*
  - *2 by MatchP1;P2*
  - *4 by Through P1-P2*
  - *=> more parameters applied than needed*

☹ Characteristics of all standards necessary

TRM - Calibration Technique

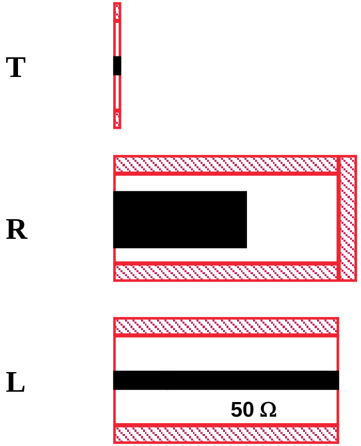
reduced Number of Standards & Parameters



- T = *Through* (*50 Ω, el. length)*
  R = *Reflect*
  M = *Match* (*50 Ω)*
- Calibration with unknown calibration standard R
- Standard R may be unknown, but must be identical for both ports
- especially suitable for test fixtures

TRL - Calibration Technique

for highest Directivity

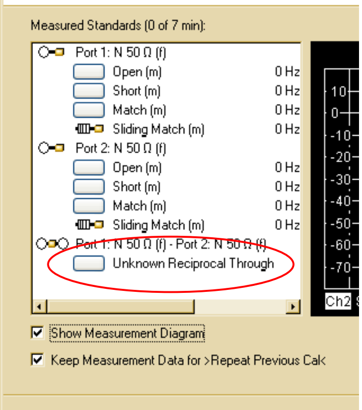


- T = *Through*
  R = *Reflect*
  L = *Line (50 Ω)*
- Calibration with unknown calibration standard R.
- Standard R may be unknown, but must be identical for both ports („reflection symmetry“)
- Impedance of the line defined by mechanical parameters, typically very accurate

UOSM: New Cal-Technique & Adapter Removal

- Effort similar to TOSM
- Unknown (but reciprocal) THROUGH means S21 = S12
- Loss, repeatability and mismatch of Through do not effect the accuracy
- Provides better effective load match than TOSM

- Purpose & Advantages
  - No data of THROUGH required
  - Any passive and cheap adapter can be used
  - Ideal for DUTs with different adapter types
  - Used as “Adapter Removal”



Differences of the Calibration Techniques

- Full two-port calibration has highest accuracy
  - UOSM and TRL provide highest accuracy
  - Corrects for all systematic errors
  - Measures the DUT in forward and reverse direction
  - Recommended for measurements in the small signal (linear) range

- One-path two-port considerably accurate
  - Corrects for mismatches between VNA output and DUT input and the transmission tracking
  - Measures DUT in forward direction only (S11 and S21)
  - => twice as fast as full two-port calibration
  - Recommended for high power applications e.g. with attenuator at port 2

- Normalization
  - Corrects for loss only(⇒ Ripple due to mismatch errors)

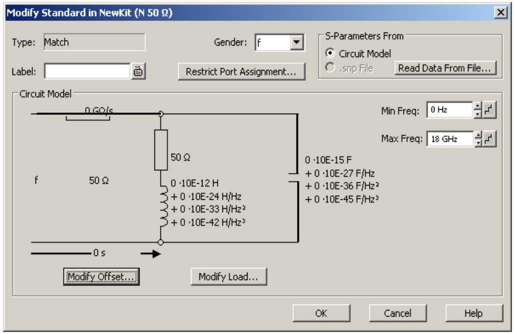
Models of Calibration Standards

Equivalent circuit model for Open Short Match

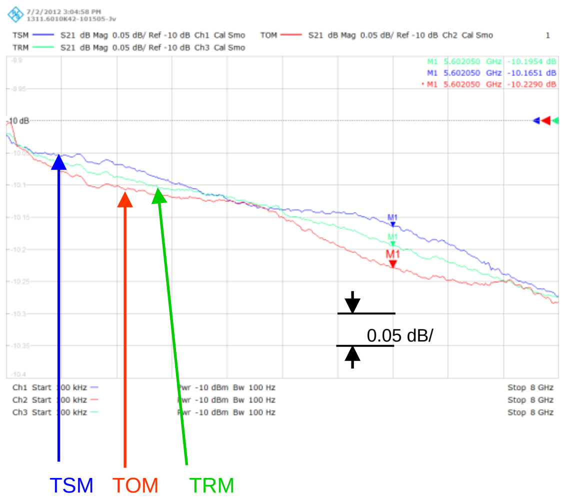
- Typically used especially for mid range and low budget kits

S-parameter model

- Definition by *.s1p or *.s2p file
- Provides most accurate description of the standards
- Accuracy does not depend on quality of standard (e.g. match) but on the accuracy used for the characterization
- TOSM and UOSM as accurate as TRL



Application & Examples
TRM vs TSM and TOM



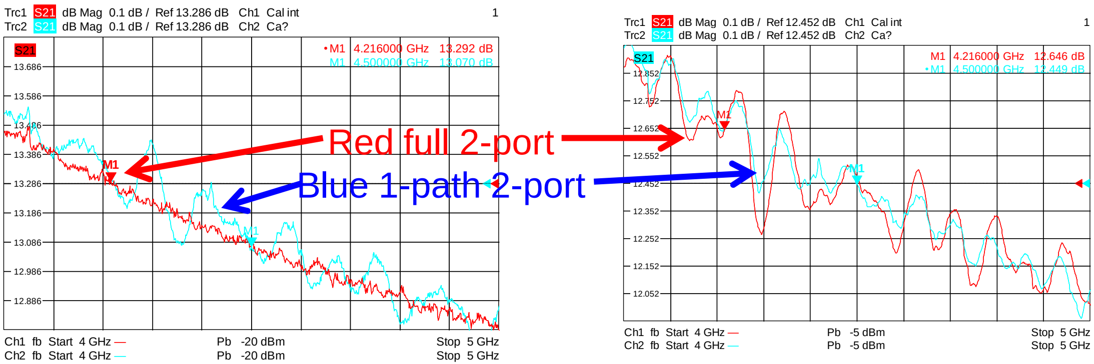
- Ripples with TSM, TOM
- Reason: Limited validity of the model description for Open and Short
- TRM requires only symmetry of the Short at Port 1 and Port 2
  - Use same Short standard at both ports

- Better effective load match with TRM
- Flat frequency response with TRM

Comparison 1-path two port - full two-port

Small signal

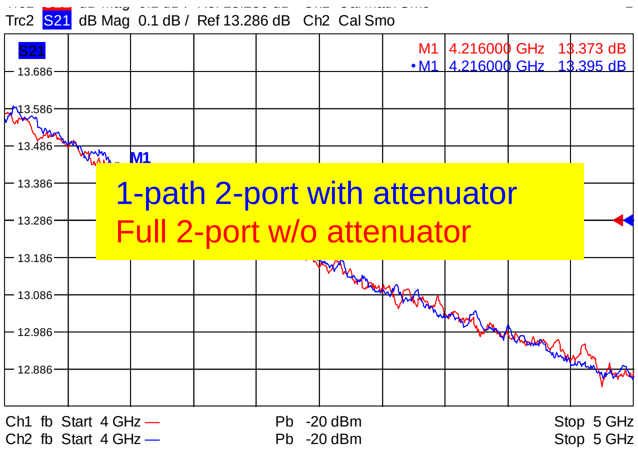
Large Signal (1 dB compression)



S12 and S22 differ between forward (large signal) and reverse (small signal) measurement of the DUT => forward and reverse error models are not valif for full-two port calibration

Comparison 1-path two port - full two-port

- Attenuator at port 2 of VNA
- Improved test port match
- Minimized error terms in reverse direction
- Same accuracy a full two port calibrated measurement



What is the best way to calibrate

- Use calibration kit based on S-parameters
  - Directivity is not limited to physical return loss of Match standard
  - Defined by the accuracy of the *.s1p file of the Match
  - Source port match does not depend onvalidity of the equivalent circuit model of Open and Short
  - Defined by the accuracy of the *.s1p file of Open and Short

- Use UOSM
  - Load port match is not limited to the return loss of the Through but defined by the reciprocity and the quality of the 1-port standards

UOSM calibration reaches the quality of a TRL calibration

END